Environmental External Costs Associated with Airborne Pollution Resulted from the Production Chain of Biodiesel in Serbia

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Abstract—**The Impact Pathway Approach was combined with Life Cycle Assessment method in order to evaluate the external costs caused by airborne emissions released during the production chain of biodiesel in Serbia. The external cost associated with the production of one metric tone of biodiesel was estimated to be 315 EUR. The positive external effects resulting from the absorption of atmospheric CO_2 by rapeseed plant can reduce the overall external cost to 181 EUR per metric tone of biodiesel. The agricultural stage is responsible for 85% of the overall external cost, in particular due to the emissions of N_2O and NH_3 from agricultural soil.**

Keywords: **external costs, biodiesel, life-cycle, Serbia**

I. INTRODUCTION

An external cost, also known as an externality, arises when the social or economic activities of one group of persons have an impact on another group and when that impact is not fully accounted, or compensated for, by the first group. Bio- and fossil diesel fuelled vehicles are an important source of emissions of many pollutants. The emission of these substances causes considerable damage affecting a wide range of receptors including humans, flora, fauna and materials. For example, a road vehicle that generates emissions of SO_2, causing damage to building materials or human health, imposes an external cost. This is because the impact on the owners of the buildings or on those who suffer damage to their health is not taken into account by the road vehicle operator.

Considerable attention has been focused recently on the assessment of external costs resulted from the tailpipe emissions of bio- and fossil diesel fuelled vehicles (for review see [1]). However, very few studies exist that have attempted to examine the external costs associated with upstream processes, i.e. with the production chain of diesel fuels in Serbia. The goal of this paper is to evaluate the external costs caused by airborne emissions released during the production chain of biodiesel in Serbia. The environmental external costs associated with emissions into water and soil, or depletion of natural resources (e.g. geological reserves of fossil fuels, land use) were not taken into account. Therefore, the estimated external cost represents the lower bound of the potential environmental external costs arising from the production of biodiesel.

In Serbian context the investigation of potential environmental and social effects of biodiesel has become increasingly important after the ratification of the South-East European Energy Community Treaty between EU and Serbia in 2006. By ratifying the Treaty Serbia has accepted the obligation to apply Directive 2003/30/EC which requires the utilization of biodiesel and other fuels from renewable sources in transport [2].

II. METHOD AND MATERIALS

A three-step procedure was adopted to calculate the external costs associated with the production chain of biodiesel.

In the first step the airborne emissions associated with each of the stages in the production chain of biodiesel were quantified using the Life Cycle Inventory (LCI) analysis. The analysis was limited to the following airborne emissions: CO_2, CH_4, N_2O, NH_3, NMVOC (non-methane volatile organic compounds), SO_2, NO_x (nitrous oxides), $PM_{2.5}$ (particles with diameter bellow 2.5 μm) and PM_{co} (particles with diameter bigger than 2.5 μm). The LCI analysis was aided by the use of the SimaPro 7 software.

In the second step appropriate damage cost factor for each of the airborne pollutant investigated was adopted. The damage cost factor represents the environmental external cost caused by the emission of a pollutant.

Finally, the overall external cost is calculated using (1).

$$EC = \sum_{i=1}^{n} EQ_i \cdot C_i \qquad (1)$$

Where:
EC – Total external cost associated with air pollution from the production chain (EUR/mt biodiesel)
EQ_i – Emission quantity of pollutant i in the production chain (kg/mt biodiesel)
C_i – Damage cost factor for the pollutant i (in EUR/kg)
n – Number (type) of airborne pollutant

A. LCI of biodiesel

The process chain for biodiesel production consists of rapeseed cultivation, grain drying, pressing and solvent extraction of rapeseed oil, refining the crude rapeseed oil, transesterification of rapeseed oil into biodiesel, and finally, distribution of biodiesel to final consumers. The main product flow normalized in terms of the production of one metric tone (mt) of biodiesel is presented in Fig. 1. Each stage of the process chain is discussed in more detail in following section.

Process description and input data

Rapeseed production. The method of cultivation and harvesting of oilseed rape modeled in this study as far as possible reflects the usual practice in Vojvodina. It was assumed that the annual yield was 2,305 kg rapeseed per hectare based on average yields of rapeseed in Vojvodina in a five year period (2005-2009). A sowing rate of 5 kg per hectare is assumed. Nitrogenous fertilizer is applied at a rate of 140 kg N/ha, corresponding to 400 kg/ha ammonium nitrate (35% N). Furthermore, the crop was fertilized with 40 kg P_2O_5/ha and 80 kg K_2O/ha, corresponding to 83 kg triple superphosphate fertilizer and 133 kg potassium chloride fertilizer, respectively. As a result of chemical and microbiological processes in the soil during cultivation, it was assumed that the air emissions of NH_3, N_2O and NO were 74 g, 35 g, and 16 g per kg nitrogen supplied, respectively [3]. Regarding pesticides, 1 kg/ha of the herbicides Fusilade forte and BOSS 300 SL were used to control weeds and 0.25 kg/ha of Megatrin 2.5 EC was used as insecticide. The emissions from the process chain of fertilizers and pesticides were calculated after [4].

For the cultivation operations, the total fuel consumption was estimated at 90 l diesel fuel (3,228 MJ) per hectare based on [5]. The air emissions associated

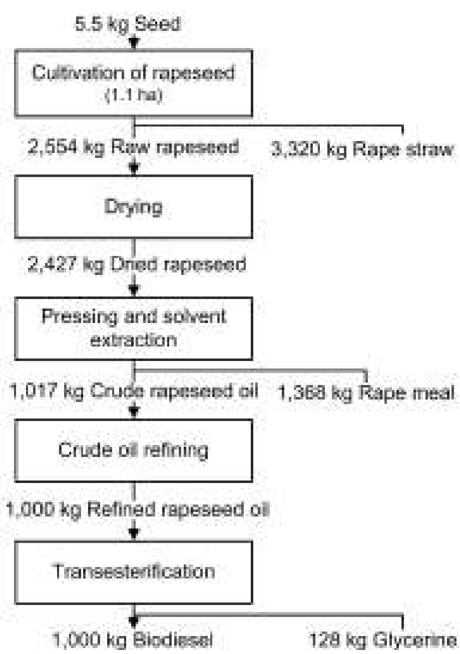

Figure 1. Main material flows related to the production of 1,000 kg biodiesel in Serbia

with the manufacturing of diesel fuel were calculated with data presented by [6] while the airborne emissions from the combustion process were taken from [7]. The volume of lubrication oil consumed was assumed to be 0.1 l/l of the diesel fuel used based on [8]. Furthermore, it was assumed that manufacturing of lubrication oil results in the same amount of emissions as manufacturing of diesel oil.

After harvesting raw rapeseed grain is transported via diesel truck to the dryer which is located 37.5 km away. Data on air emissions associated with the combustion of diesel fuel in a truck were taken from [9].

Seed drying. In Vojvodina oilseed is harvested with a typical moisture content of 13.5%, which must be reduced to at least 9% as a requirement for the oil extraction facilities, and to ensure stability in storage [10]. It is assumed that the drying process takes place at a vertical gravity dryer Strahl 5000 FR (Officine Minute, Italy) powered by fuel oil and three electric fans of overall installed capacity of 54 kW. According to [10] the heat requirement of the process is 260 MJ/mt of dried grain and electricity is consumed at a rate of 2.7 kWh/mt of dried grain. The data source regarding airborne emissions associated with electricity and heat generation are specified in Table 1. The dried grain is transported via diesel truck to the oil mill plant which is located 37.5 km away.

Solvent extraction and oil refining. After the drying process, typical oilseeds contain 40-44% oil and 54-58% high protein meal [11]. The oil is extracted from the dried rapeseed by solvent extraction which is the most dominant technology in the rapeseed oil industry. The material and energy requirement of the process is based on data presented by [11]. The process involves seed cleaning, cooking and flaking, before the seed is in an appropriate state for mechanical pressing to remove a proportion of the oil. After mechanical pressing, the rape meal still contains a significant amount of oil; counter-current solvent extraction of the meal with hexane is used to reduce this oil content to ca. 2%. The only material used in the solvent extraction is hexane at a rate of 1.19 kg per mt of crude rapeseed oil. The heating requirement of the plant is provided by steam produced from light fuel burned in industrial boiler, using 43 kg (1,797 MJ) light fuel oil/mt crude rapeseed oil produced. Electricity is required at 419 MJ/mt of crude oil produced.

In the refining step the phospholipids from the crude rapeseed oil are removed by the addition of phosphoric acid (H_3PO_4). The remaining free fatty acids are converted to soap by the addition of sodium hydroxide, and removed using a centrifuge. Other impurities are removed via filtration using acid treated natural clay. Data on material and energy requirement of the refining process is available from [11]. Light fuel oil is required at 6.1 kg/mt crude oil to provide the refining plants' heating and electricity is required at 104 MJ/mt of refined oil. The refined oil is transported with diesel truck to the nearby transesterification plant located 1 km away.

Transesterification. The transesterification of refined rapeseed oil into biodiesel takes place at a state of art biodiesel production facility with annual production capacity of 100,000 mt of biodiesel. The transesterification process is performed with methanol in the presence of sodium methoxide as an alkali catalyst. The material and energy inputs of the process are described in [12]. The emissions to air during the transesterification process were assumed to be negligible. After the transesterification process biodiesel is transported to the final consumer located 25 km away.

Tab. 1 gives an overview of processes included in the LCI of biodiesel with specification of material and energy inputs and references to data sources used.

LCI assumptions

Allocation procedure. The production of biodiesel generates by-products like rape straw, rape meal and glycerol (Fig. 1). The purpose of allocation is to determine how a particular environmental burden, e.g. CO_2 emission, should be shared amongst the biodiesel and the by-products. The allocation procedure adopted in this study is based on economic allocation, i.e. the overall environmental burden of the system is shared amongst biodiesel and by-products proportionally to their share in the overall revenue of the system. The market prices used to calculate the revenues from biodiesel and co-products are as follows: 265 EUR/mt of raw rapeseed, 28 EUR/mt of rape straw, 730 EUR/mt of refined oil, 170 EUR/mt of rape meal, 900 EUR/mt of biodiesel, and 80 EUR/mt of glycerol.

Accounting for CO_2 absorbed by the plant. A certain amount of carbon from the air is absorbed by the plant during the process of photosynthesis. This carbon can be accounted for as a positive externality and eventually subtracted from the overall external costs of biodiesel production chain. According to [19] the carbon content of raw rapeseed grain is 58.4% on a mass basis. Under the assumption that all of the carbon is absorbed from the atmosphere it can be calculated that during the production of 2,554 kg raw rapeseed grain 1,491 kg of carbon is absorbed, corresponding to 5,469 kg of CO_2. Of the 1,491 kg of carbon taken up by the rapeseed plants in the agriculture stage, we take credit for only 736 kg of carbon; which equals the biomass-derived carbon content of 1,000 kg biodiesel fuel [3]. This is equivalent to 2,700 kg of CO_2 removed from the atmosphere for every mt of biodiesel produced. The remaining uptake of CO_2 is associated with by-products in the production chain of biodiesel (i.e. rapeseed meal and glycerine). We did not feel it was appropriate to take credit for this carbon.

TABLE I.
MATERIAL AND ENERGY INPUTS IN THE PRODUCTION CHAIN OF BIODIESEL

Stage in the production chain	Source of airborne emission	Inputs of material and energy		Source of data on emissions
		Unit	Quantity	
Rapeseed cultivation and harvesting	Production and use of ammonium nitrate fertilizer	kg N/ha	140	Ref. [4]
	Production of triple superphosphate fertilizer	kg P_2O_5/ha	40	Ref. [4]
	Production of potassium chloride fertilizer	kg K_2O/ha	80	Ref. [4]
	Production of pesticides	kg/ha	1.25	Ref. [4]
	Production of sowing seeds	kg/ha	5	Ref. [4]
	Production and combustion of diesel fuel in agricultural machinery	MJ/ha	3,228	Ref. [6, 7]
	Production of lubrication oil	MJ/ha	322	Ref. [6]
	Transport of rapeseed grain to dryer via diesel truck	tkm/ha	173	Ref. [9]
Drying of the rapeseed grain	Production and combustion of light fuel oil for process heating	MJ/mt of dried seed	260	Ref. [6]
	Production of electricity	kWh/mt of dried seed	2.7	Ref. [13]
	Transport of dried grain to oil mill via diesel truck	tkm/mt of dried seed	75	Ref. [9]
Pressing and solvent extraction	Light fuel oil production and combustion in steam boiler	kg/mt of crude oil	43	Ref. [6]
	Production of electricity	MJ/mt of crude oil	419	Ref. [13]
	Production of hexane	kg/mt of crude oil	1.19	Ref. [14]
Crude oil refining	Production of electricity	MJ/mt of refined oil	104	Ref. [13]
	Light fuel oil production and combustion in steam boiler	kg/mt of refined oil	6.2	Ref. [6]
	Production of phosphoric acid (85% in H2O)	kg/mt of refined oil	0.8	Ref. [15]
	Production of sodium hydroxide (50% in H2O)	kg/mt of refined oil	2.1	Ref. [15]
	Production of sulphuric acid (100%)	kg/mt of refined oil	1.9	Ref. [15]
	Production and consumption of bentonite (clay)	kg/mt of refined oil	9	Ref. [16]
	Transport of refined oil to biodiesel plant via diesel truck	tkm/mt of refined oil	1	Ref. [9]
Transesterification of refined oil into biodiesel	Production of electricity	kWh/mt of biodiesel	12	Ref. [13]
	Natural gas production and combustion in industrial boiler	MJ/mt of biodiesel	1,236	Ref. [17]
	Production of sodium methoxide (100%)	kg/mt of biodiesel	5.0	Ref. [18]
	Production of sodium hydroxide (50% in H2O)	kg/mt of biodiesel	1.5	Ref. [15]
	Production of hydrochloric acid (36% in H2O)	kg/mt of biodiesel	10	Ref. [14]
	Production of methanol	kg/mt of biodiesel	96	Ref. [15]
	Transport of biodiesel to filling station via diesel truck	tkm/mt of biodiesel	50	Ref. [9]

B. External cost resulting from the exposure to airborne pollutants

The external cost associated with a particular airborne pollutant (except greenhouses gases) was estimated using the EcoSenseWeb software [20]. The EcoSenseWeb was developed to support the assessment of impacts on human health, crops, building materials and ecosystems resulting from the exposure to airborne pollutants. The estimation of external costs in EcoSenseWeb is based on the Impact Pathway Approach (IPA) methodology developed in the ExternE Project funded by the European Commission [21]. The IPA starts with the emission of an airborne pollutant at the location of the source into the environment. It models the dispersion and chemical transformation in the different environmental media. Introducing receptor and population date it identifies the exposure of the receptors and calculates the impacts. These impacts are then weighted and aggregated into external costs. The external cost caused by the emission of 1 kg of NH_3, NMVOC, NO_x, PM_{co}, $PM_{2.5}$ and SO_2, was estimated to be 10.21 EUR, 0.76 EUR, 6.95 EUR, 0.64 EUR, 16.31 EUR and 6.95 EUR, respectively.

There is considerable uncertainty attached to the estimation of damage costs of greenhouse gases, given the long-time scales involved, and the lack of consensus on future impacts of climate change itself. The damage cost factors for CO_2 range from 19 EUR [21] to 80 EUR per mt CO_2 [22]. In this study we adopted a central value of 50 EUR/mt of CO_2. The external costs for other greenhouse gases (i.e. CH_4 and N_2O) are calculated by multiplying the damage cost factor of CO_2 with the global warming potential factor of CH_4 and N_2O. According to [23] the global warming potential factors of CH_4 and N_2O are 23 and 296, respectively.

III. RESULTS AND DISCUSSION

Environmental external cost associated with airborne pollution resulted from the production chain of biodiesel was estimated to be 316 EUR per mt of biodiesel produced, corresponding to 0.008 EUR/MJ. Positive external effects resulting from the absorption of atmospheric carbon dioxide by plant can reduce the overall external costs to 181 EUR per mt of biodiesel produced (Tab. 2). The agricultural stage is responsible for 85% of the overall environmental external costs associated with the production of biodiesel. Even if the positive external effects from the absorption of atmospheric carbon dioxide are entirely assigned to the agricultural stage this stage would still have a significant share (ca. 75%) in the overall environmental cost. Processes associated with the solvent extraction and crude oil refining are causing 8.5%, while the transesterification stage is responsible for 4% of the overall environmental damage caused by the production of biodiesel. The environmental externalities associated with the grain drying stage are less significant.

The relative contributions from different processes which contribute to biodiesel production are illustrated in Fig. 2. In the agricultural stage emissions (N_2O and NH_3) from agricultural soils are causing 54% of the environmental external costs. The remaining part of the environmental external costs in the agricultural stage is associated with airborne emissions from the production of fertilizers (31%) and from the production and combustion of diesel fuel in agricultural machinery (14%).

Airborne emissions associated with the production and combustion of light fuel oil and the production of electricity are responsible for two thirds of the overall environmental external cost caused in the grain drying process. In the oil mill stage the airborne emissions from the production and use of the energy required by the plant are causing 98% of the environmental external costs. Chemicals used during the solvent extraction and the refining process have a minor influence on the results (ca. 2%). Emissions associated with the production of chemicals contribute the most to the overall external cost of the transesterification process, followed by the production and use of the energy required by the plant. The high share of external costs associated with chemicals is mainly due to the significant amount of CO_2 released during the manufacture of methanol.

Fig. 3 shows the relative contribution of each of the investigated airborne pollutant to the overall external costs of the production chain. Greenhouse gases cause around 45% of the overall external cost associated with the production chain of biodiesel. From other pollutants significant share have external costs from the emission of NH_3, which is almost entirely related to the application of nitrogenous fertilizer in the agricultural stage, and NOx and SO_2, mainly released during the combustion of fossil fuels.

IV. CONCLUSIONS

The environmental external costs associated with airborne emissions from biodiesels` production chain are considerable. The agricultural stage is responsible for 85% of negative externalities associated with the

TABLE II.
AIRBORNE EMISSIONS AND ASSOCIATED EXTERNAL COSTS IN THE PRODUCTION CHAIN OF BIODIESEL

Production chain of biodiesel	Airborne emissions released during the production chain of biodiesel (kg per mt biodiesel)									External costs per mt biodiesel
	CO_2	CH_4	N_2O	NH_3	NMVOC	NO_x	SO_2	$PM_{2.5}$	PM_{co}	
Rapeseed production	677.7	1.12	5.57	8.27	0.61	6.41	2.08	0.52	0.52	270 EUR
Grain drying	71.5	0.07	0.00	0.00	0.06	0.21	0.16	0.02	0.02	7 EUR
Solvent extraction and refining	224.1	0.15	0.00	0.00	0.08	0.28	1.52	0.19	0.10	27 EUR
Transesterification	155.3	0.57	0.00	0.00	0.13	0.21	0.31	0.03	0.04	13 EUR
Total	1128.7	1.91	5.57	8.27	0.89	7.12	4.08	0.75	0.68	316 EUR
Total (less the absorbed CO_2)	-1571.2	1.91	5.57	8.27	0.89	7.12	4.08	0.75	0.68	181 EUR

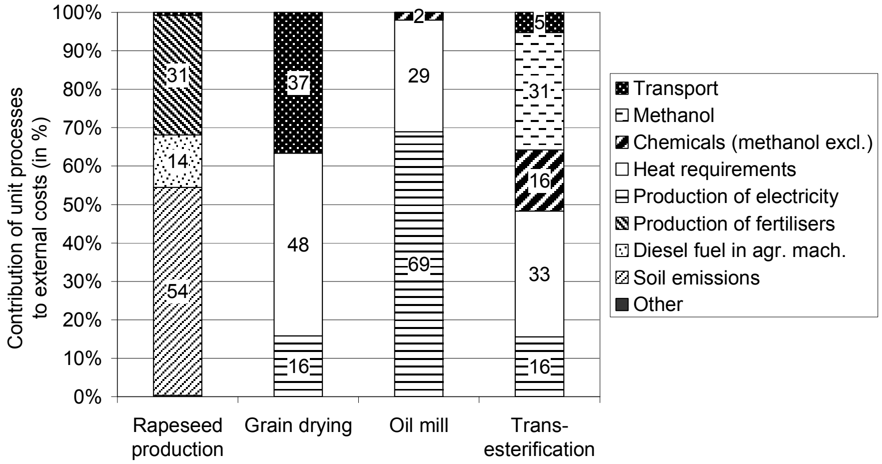

Figure 2. Relative contributions of the unit processes to the external cost of the production chain

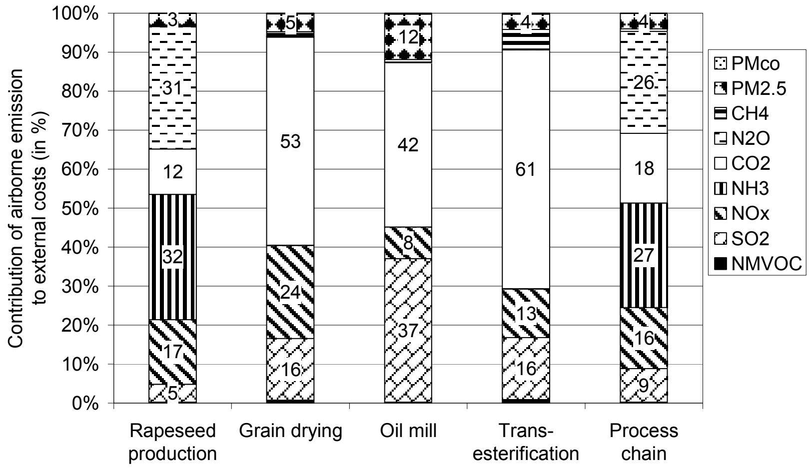

Figure 3. Relative contributions of a particular airborne emission to the overall external cost of the production chain

production chain of biodiesel. It has been shown that field emissions of N_2O and NH_3 have a major contribution to the environmental external cost of the agricultural stage. This result suggests that previous estimates that have not taken into account the impacts of soil emissions have significantly underestimated the environmental impact of biodiesel.

Both converting processes (rapeseed to oil, oil to biodiesel) consume a large volume of energy resulting in significant CO_2 emissions. Since the modeling reflects state-of-art technology it is based on the consumption of fuels of fossil origin. Thus, this step currently contributes significantly to the overall environmental burden but allows replacing with alternative, e.g. renewable energy sources. This may be particularly valid for the replacement of the light fuel oil as a heating source.

An opinion worth of discussion is the possibility of using bioethanol instead of fossil methanol (made from natural gas prevailingly) in the transesterification of the rapeseed oil.

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